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PLATE RESPONSE ANALYSIS USING SHOCK TUBE

JOSEPH M. SANTIAGO

NOVEMBER 1987

US ARMY BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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1. INTRODUCTION

The deformation of structures due to blast is of concern because of the severe damage that can ensue. An important tool in predicting the response of structures to blast has been the computer code, either used by itself or in conjunction with experiments. This raises the problem of assessing the accuracy of numerical results. Because in most real situations the structure is complex and the response is often nonlinear, there are no analytical solutions available with which to make comparisons and the accuracy of a numerical solution has to be evaluated experimentally. The validity of such an evaluation often hinges on the precise determination, both spatially and temporally, of the loading imposed on the structure and the accurate characterization of the constitutive properties of the materials used in the structure[1]. Moreover, even for the relatively simple case of flat plates, there are problems associated with realizing idealized boundary conditions experimentally and recording loading functions accurately[2,3]. Measuring loads accurately can be especially difficult when the blast results from the detonation of an explosive located close to the structure[4].

Shock tubes have been employed as one means of defining loads precisely, either directly by mounting pressure gauges on a non-responding fixture during the test[5] or indirectly by the use of a non-responding model of the structure instrumented with pressure gauges[1]. This report presents the results of an investigation into the suitability of a small shock tube facility for performing highly precise plate response experiments in which large deflections and elastic-plastic deformations are experienced. The objectives were to determine how well the shock tube resolved the problem of precisely defining the loading imposed on the plate, to evaluate the accuracy of a finite-difference structural response code in predicting large transient deflections, and to assess the performance of an optical displacement follower in measuring highly transient deflection histories.

2. DESCRIPTION OF TESTS

The tests were conducted at the Ballistic Research Laboratory's small shock tube facility[6]. The test arrangement is schematically shown in Figure 1. The tube has a 102 mm by 381 mm (4 inch by 15 inch) rectangular test section at the open end, which for this test series was sealed off by hydraulically clamping the plate specimens there. This exposed a 102 mm by 381 mm rectangular area of the specimen to a more or less constant reflected shock pressure for approximately 4 to 6 milliseconds during the tests. The specimens themselves were 254 mm by 534 mm (10 inch by 21 inch) rectangular plates of 2SO aluminum in two thicknesses: 0.508 and 0.813 mm (0.020 and 0.032 inches). Initial tests showed that the 76 mm margin provided for clamping the plates was not sufficient to prevent slipping under load, and it was necessary to machine matching crimping channels into the faces of the clamping surfaces to mechanically secure the plates.

The OPTRON optical displacement follower[7] was used to record the time history of the deflection at the center of the plate. This instrument senses displacements by measuring changes in the intensity of light. For these tests, the OPTRON instrument was mounted outside the shock tube immediately after the test section and pointing through windows in the sides of the tube toward a light source on the opposite side, as shown in Figure 1. A light-weight balsa block was fixed to the center of the plate to project into the field of view between the OPTRON and the light source, in this way restricting the amount of light falling on the instrument as a function of the plate displacement.

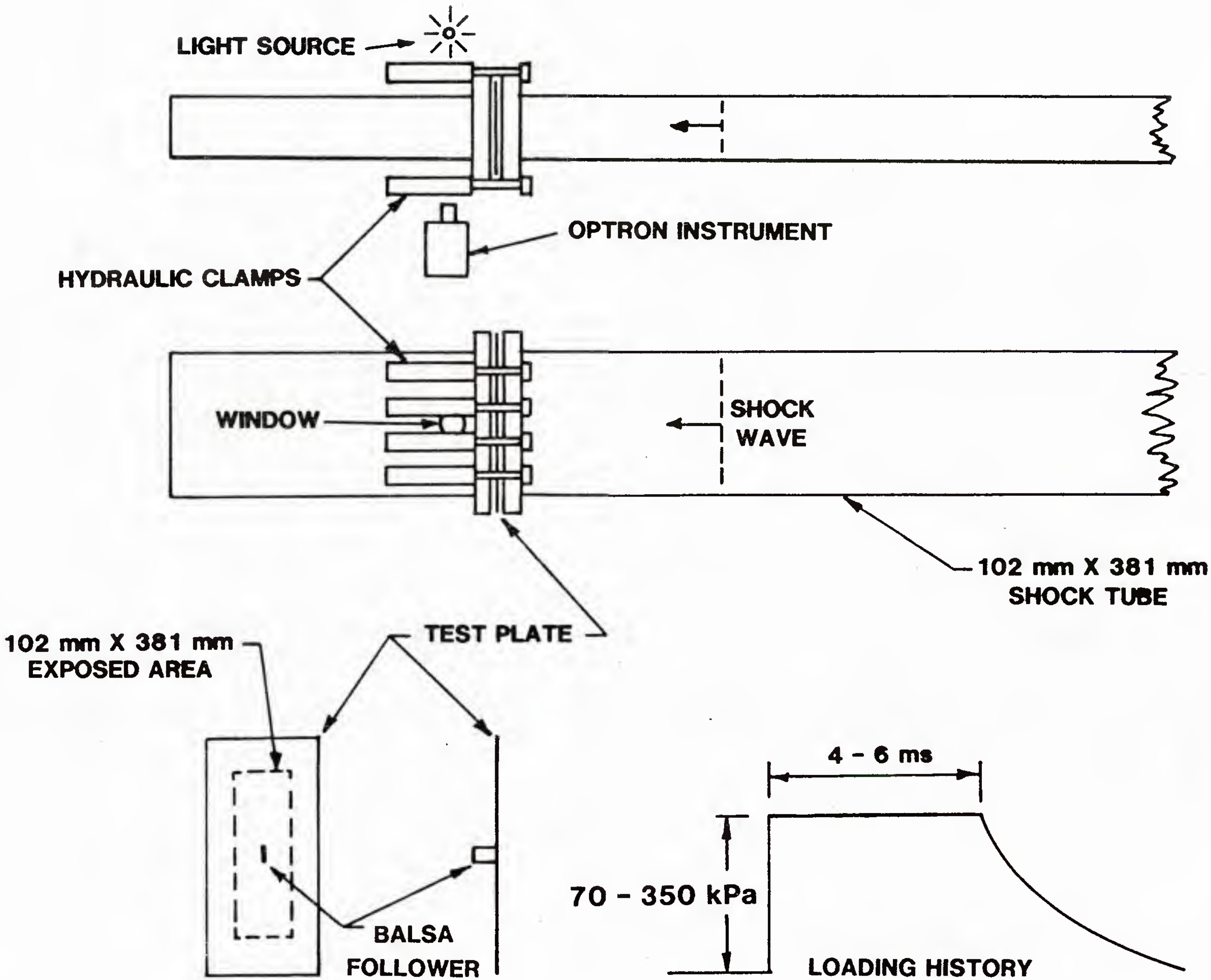

Figure 1. Schematic of the shock tube arrangement for the plate response experiments.

The tests were performed over a range of pressures to assure that the specimens would undergo moderate to large deflections without rupturing. This was facilitated by the relatively high ductility of the specimen material. It was found that the OPTRON did not always produce acceptable records of the deflection histories. However, a sufficient number of relatively clean records were obtained for each plate thickness to permit comparison with code calculations for three distinct levels of pressure, summarized in Table 1.

3. DESCRIPTION OF COMPUTER CODES

The REPSIL[8] and the RPSL1D[9] computer codes were chosen for the comparison because they treat the large deformation of plates and shells without restrictions as to magnitude, they are reasonably straightforward to use, and our experience has shown them to be accurate and reliable. The REPSIL code is a finite difference program that treats the finite transient deformation of thin shells based on the Kirchhoff assumption. The RPSL1D code is a one dimensional version of the REPSIL code that reduces the intrinsic shell coordinates from two to one dimension by the assumption of either plane strain or axisymmetric deformations. Both codes use a second order accurate spatial scheme to approximate the shell equations and a centered time scheme to explicitly integrate the equations of motion. As is usual with an explicit time scheme, the size of the time step must be restricted to maintain numerical stability[11].

Both codes have a fairly advanced capability for modeling elastic-plastic behavior. The so-called *mechanical sublayer* model[12] is used to simulate nonlinear kinematic hardening in a piece-wise linear manner. To simulate strain rate hardening, a hardening law of the form[13]

$$S_y = S_o \left(1 + \frac{\dot{e}}{D}^{\frac{1}{p}} \right) \tag{1}$$

is used to amplify the value of the static yield stress, S_o, as a function of the second invariant of the deviatoric strain rate tensor, $\dot{e}$, to give an augmented dynamic yield stress, S_y, (D and p are material parameters). Figure 2 shows a typical polygonal fit used by the mechanical sublayer model to simulate the nonlinear hardening curve and corresponding amplification produced by the strain rate hardening law. This latter feature was explored as a means of effecting a closer correspondence between test results and calculations.

The codes accept surface pressure loading that can vary in space and in time, automatically adjusting the direction of load application to compensate for the change in the orientation of the surface normal as the shell undergoes finite deformations. Initial calculations were carried out assuming that the pressures imposed on the plate remained constant at the values of the peak reflected shock pressures listed in Table 1. Subsequently, a *piston theory*[10] type of velocity dependent correction, based on the equation

$$P_r - P_a = P_r^o - P_a^o - (\rho_r^o\, c_r^o + \rho_a^o\, c_a^o)\, V_n \tag{2}$$

was programmed into RPSL1D, where P denotes pressure, ρ density, c sound speed of air, and V_n is the current normal velocity of the plate, while the superscript o refers to the nominal (constant) values and the subscripts r and a to values on the front or reflected side of the plate and on the back or ambient side, respectively.

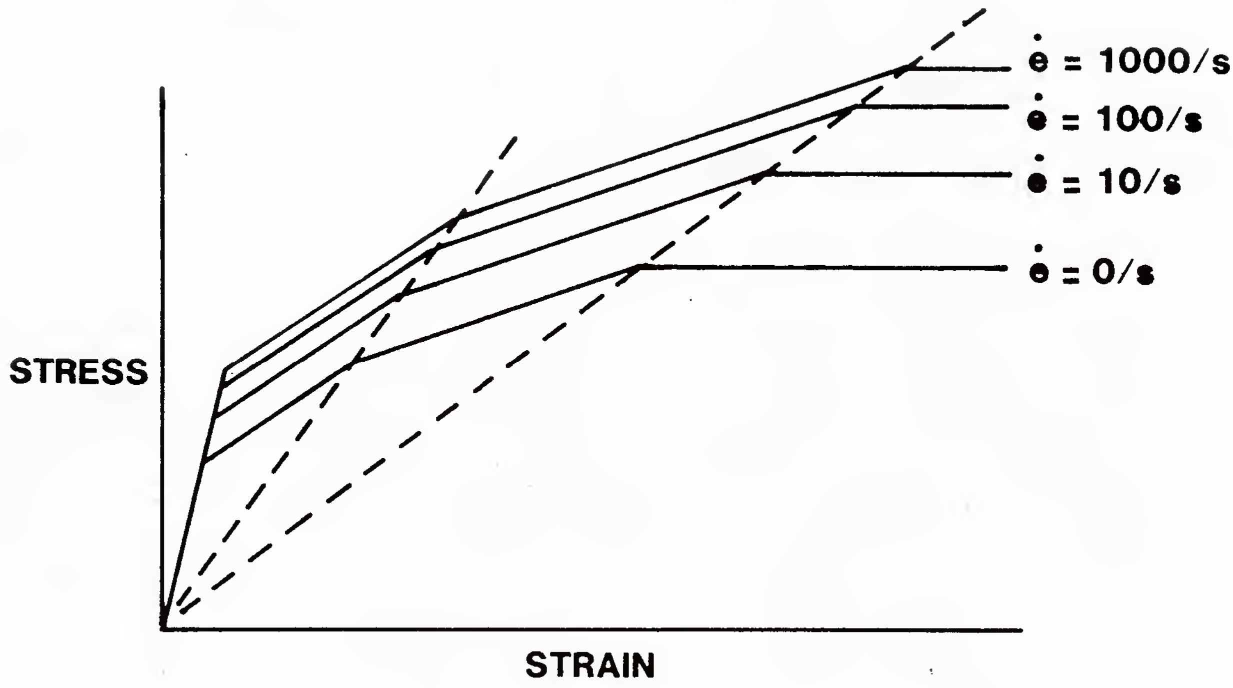

Figure 2. Amplification of piecewise linear static stress-strain curve produced by the strain rate hardening law.

4. MECHANICAL PROPERTIES OF PLATE SPECIMENS

The elastic properties of the plate specimens were taken as the nominal values for aluminum:

Young's Modulus $= 69$ GPa (10^7 psi)
Poisson's Ratio $= 0.3$
Mass Density $= 2700$ kg/m^3 (.000253 lb-s^2/in^4)

The elastic-plastic properties were determined from a series of tensile tests performed using an INSTRON machine. The typical tension specimens, 356 mm in length and 38 mm in width in the test section (i. e., away from the grips) were cut for each thickness of plate.

Initial tests indicated that the plates were not entirely isotropic as a result of the rolling process used during manufacture and it was necessary to test specimens cut parallel and perpendicular to the rolling direction. It also was found that, as a result of the low strength of the aluminum and the relative thinness of the specimens, the strain gauge and the adhesive used to bond it to the test section locally strengthened the specimen and produced an artificially high stress-strain curve. This problem forced us to abandon strain gauge techniques in favor of less accurate means of measuring extension. However, to assure validity of results, two independent means were used: a visual method based on taking photographs of markings on the surface of the tension specimen and a mechanical method using a cathetometer.

The resulting tensile test data, depicted in Figure 3, clearly show the anisotropy of the specimens and the different material properties for the two thicknesses. The data are plotted as Cauchy stress versus Almansi strain[14], in agreement with the variables that the REPSIL and RPSL1D codes accept as input. Also shown are the polygonal simulations of the nonlinear hardening curves employed in the codes. Since for some aluminums strain rate dependent

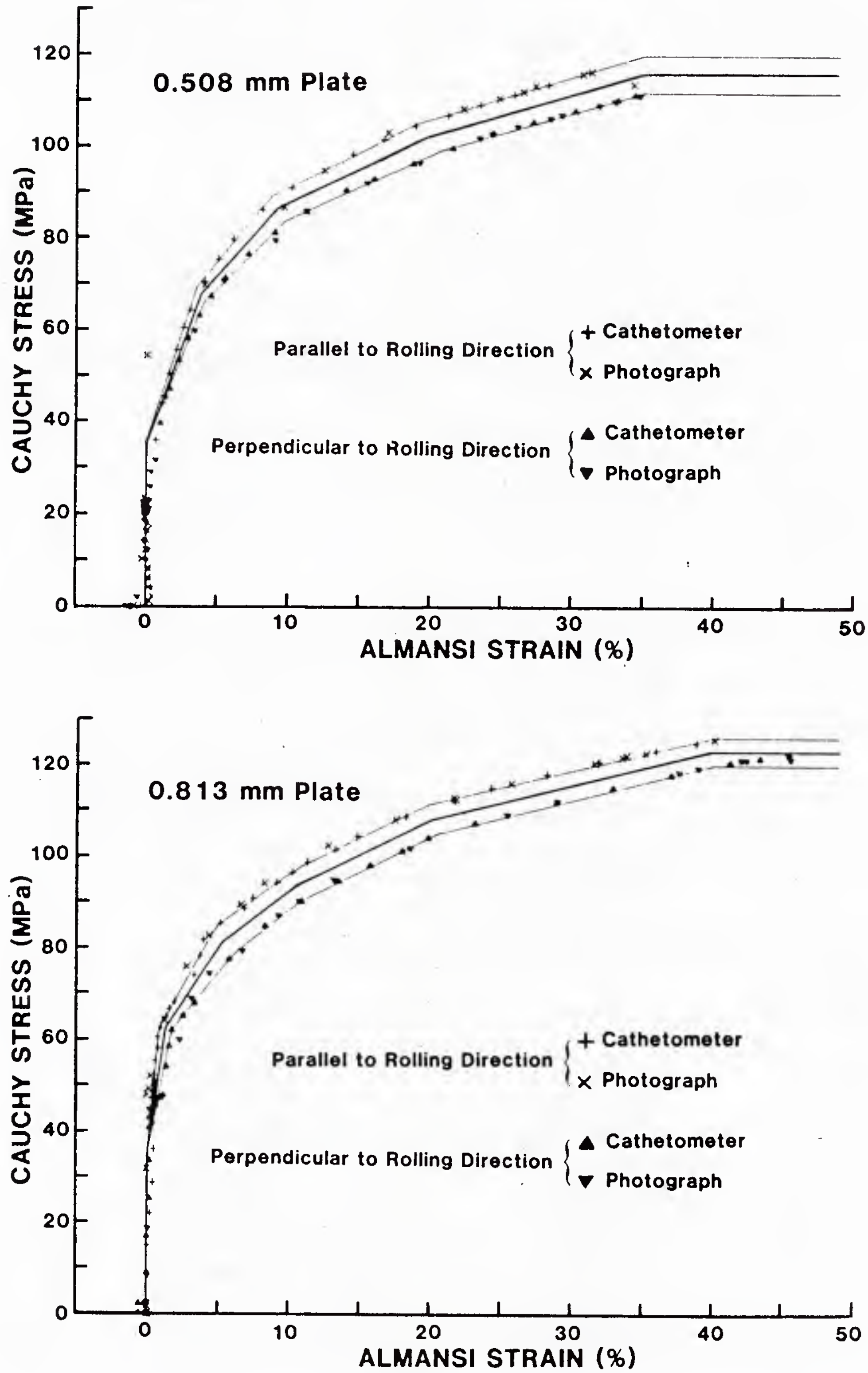

Figure 3. Piecewise linear fits to tensile test data used by mechanical sublayer model.

hardening during plastic flow can be significant, see Huffington & Wortman[15] for an interesting attempt to quantify this phenomena, it was decided to employ the strain rate hardening model in the codes. However, because no dynamic material data were available, nominal values of $p = 4$ and $D = 6500$ for 6061-T6 aluminum, as published by Symonds[16], were used for the rate hardening parameters in equation (1).

5. CONVERGENCE STUDY

A convergence study was carried out to investigate the possibility of replacing a model of the entire plate by a model of a plane strain lateral cross-section and to determine the degree of mesh refinement needed to accurately predict deflections. Advantage was taken of the problem's two planes of symmetry to model one quarter of the entire plate with the REPSIL code, with the mesh divisions in the longitudinal direction refined from 5 to 18, while the divisions in the lateral direction were held fixed at 5. This is shown in Figure 4 for the deformed mesh at maximum deflection. Calculations were performed for a reflected pressure of 332 kPa on the 0.508 mm thick plate. The first maxima of the lateral strains and normal deflections at the center of the plate (which occurred at 540 microseconds) were compared for the three mesh sizes and found to be virtually unaffected by the refinement. Moreover, as the mesh was refined, the longitudinal strain at the center was found to approach a value of zero. These results justified using the RPSL1D code to perform a plane strain analysis of the cross-section in place of the REPSIL model of the plate.

Again, based on symmetry, the RPSL1D code modeled one half of the lateral cross-section of the plate, with the mesh divisions refined from 5 to 40, as shown in Figure 5 for the mesh at maximum deflection. As before, a reflected pressure of 332 kPa was applied to the 0.508 mm thick plate. For the initial calculations, the engineering stress versus engineering strain curve was employed. The first maxima of the deflection at the center of the plate (occurring at between 538 and 546 microseconds) were plotted as the mesh was refined and, as shown in Figure 6, were found to converge more or less linearly to a value of 24.3 mm. Although the value was considerably more than the 19.6 mm recorded in the test at 332 kPa reflected pressure, this was not entirely surprising, since at the large strains calculated, the Cauchy stress-Almansi strain curve called for by the code should have been used.

Hence, with the slope of convergence established, calculations proceeded using the 10 mesh model since it predicted a deflection within 0.5% of convergence, a value well within the estimated range of experimental error. Using the exact Cauchy stress-Almansi strain curve as input, the increase in apparent stiffness gave a maximum deflection corresponding to a converged value of 22.4 mm, still somewhat more than the experimental value (Figure 6). Repeating the calculation using the piston theory pressure correction, a significant improvement was achieved with a predicted converged maximum deflection of 19.9 mm, within 2% of the test result. Repetition of the last calculation with the addition of the strain rate hardening resulted in a converged maximum deflection of 17.1 mm, considerably lower than the test result. The results summarized in Figure 6 show that:

- the strains undergone by the plate were large enough to require the use of the exact Cauchy stress-Almansi strain curve,
- it is necessary to correct the pressure imposed on the plate for the effects of plate motion,
- the strain rate hardening model using the nominal values of the material parameters exaggerates hardening effects.

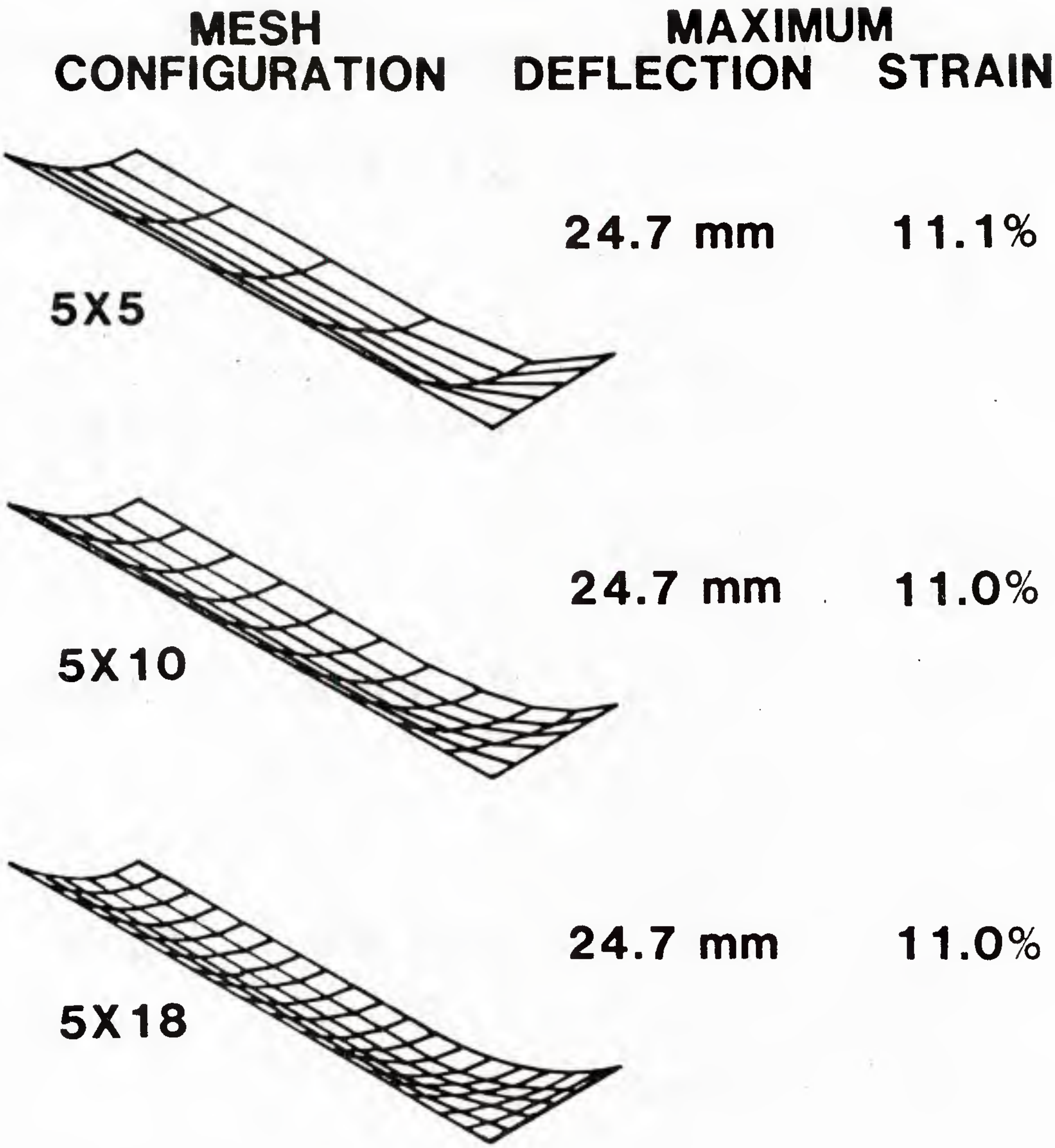

Figure 4. Longitudinal mesh refinement used by the REPSIL code for convergence study.

The last two items deserve further discussion. Piston theory and strain rate hardening were applied individually in this and subsequent calculations and were found to have approximately the same quantitative effect in reducing deflections, although strain rate hardening dampened peaks somewhat more. However, because the strain rate hardening parameters employed were for 6061-T6 rather than 2SO aluminum, less reliance was placed on the results using this model than the piston theory model, which at least employed parameters in equation (2) corresponding to the experiments. Moreover, it has recently been pointed out to the writer[17] that 2SO aluminum is particularly rate insensitive and that the use of the 6061-T6 parameters most likely exaggerated the effects of rate sensitivity.

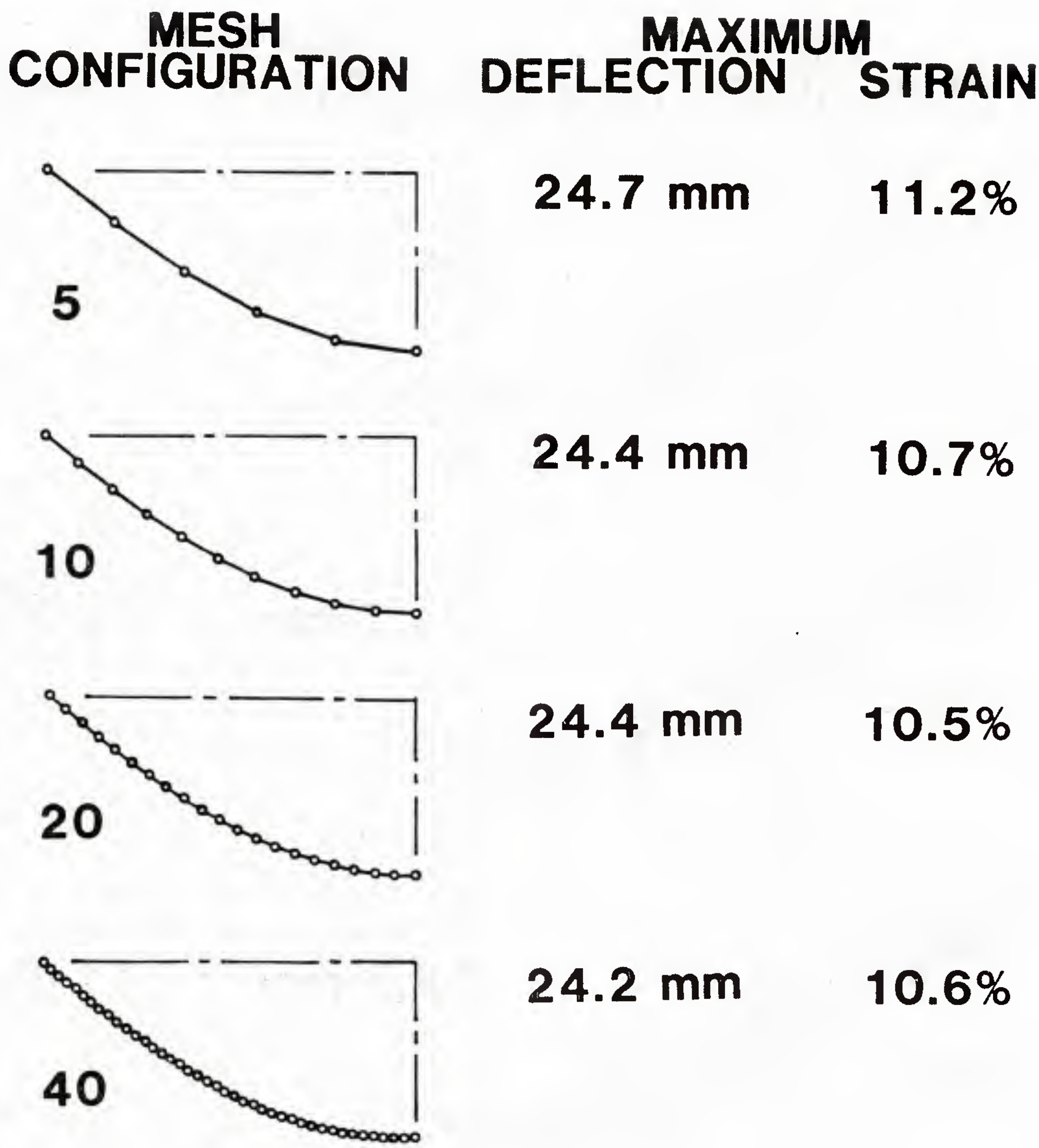

Figure 5. Cross-sectional mesh refinement used by the RPSL1D code for convergence study.

6. CORRELATION OF TEST RESULTS AND COMPUTATIONS

Once the convergence study had demonstrated that the plane stress model using 10 mesh points would calculate deflections with sufficient accuracy, calculations were undertaken to match a series of tests in which the pressure loading levels had been adjusted to give a graduated increase in the deflections and the amount of plasticity. As already mentioned, not all the deflection histories recorded by the OPTRON were acceptable, but relatively clean records were obtained corresponding to three distinct levels of pressure for each plate thickness, as shown in Table 1. RPSL1D calculations were performed for these pressures under the three following conditions:

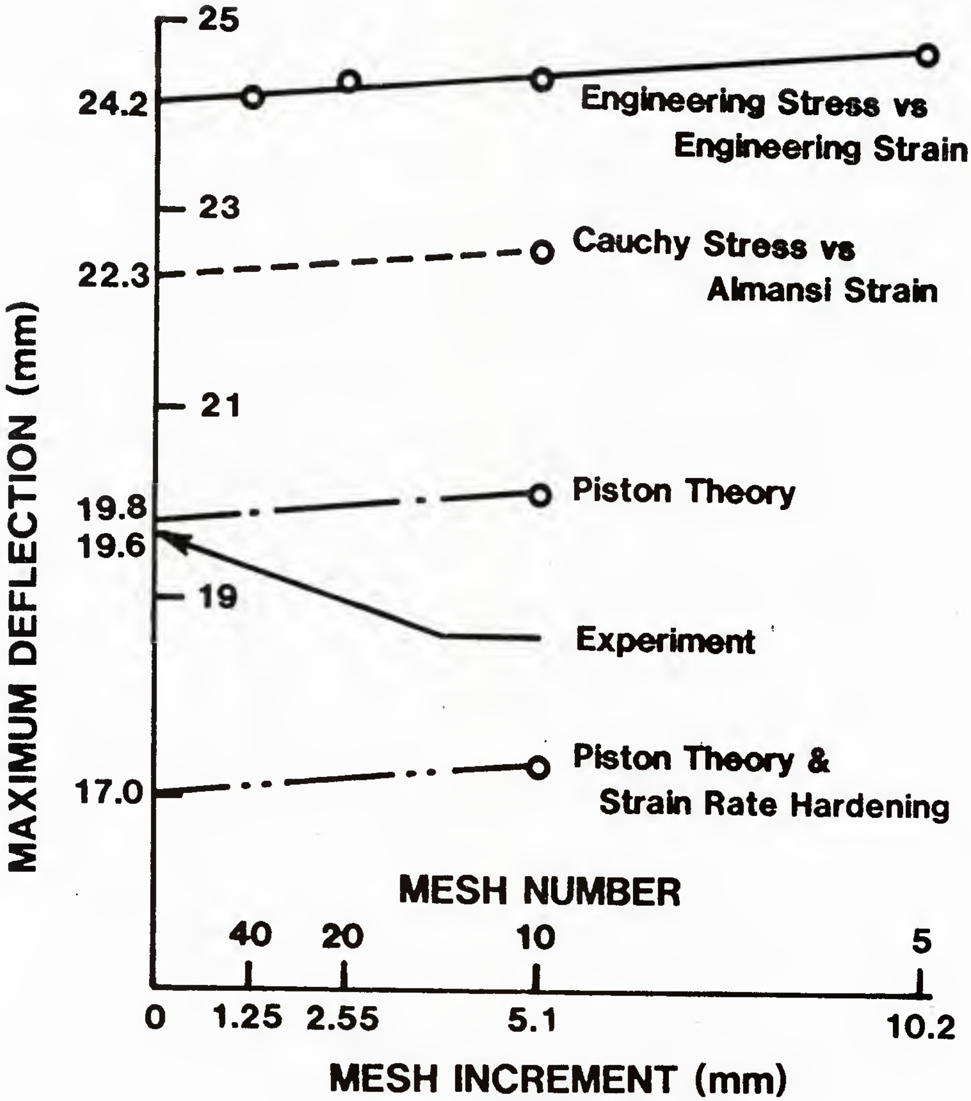

Figure 6. Comparison of converged values of computed maximum deflections with experimental result.

- maintaining the reflected pressure constant at its peak value,
- applying the piston theory correction to the pressure loading,
- in addition, using the strain rate hardening model.

The correct Cauchy stress-Almansi strain hardening curves corresponding to each plate thickness, as obtained by averaging the data parallel and perpendicular to the rolling direction, Figure 3, were used.

The comparisons between computed and experimental deflection histories at the center of the plates are summarized in Figures 7 to 12. It should be remarked that though the experimental records do show some noise, this is most likely due to natural vibrations in the test apparatus, since noise can be detected in the records before the shock reflects from the plate. It can be seen that the OPTRON instrument performed very well on the tests with the 0.508 mm plates, with the amplitude of increased noise never exceeding 8% of the maximum deflection. On the tests with the 0.813 mm plates, its performance was poorer. At the lowest pressure, 148 kPa, some malfunction clearly occurred just after the first maximum, although the crests of the measured deflections appear to have some resemblance to reality. Our experience has shown the OPTRON to be a fairly reliable instrument, although there is the possibility that perhaps it was not solidly anchored for this test. A more likely explanation is that the balsa follower tore partially loose, enabling it to intermittently swing out of the field of view of the OPTRON and thus causing the instrument to register apparently reduced instantaneous deflections. At the next level, 222 kPa, the record is better, but still shows two unaccountable spikes near the first and second maxima. Although there is a slight possibility that stress waves reflecting back and forth in the follower may have caused the spikes, this is hardly likely since no other records exhibit similar spikes. On the other hand, the record at the highest pressure, 339 kPa, for the 0.813 mm plate is as good as those obtained with the 0.508 mm plates. Hence, the anomalies in the 0.813 mm plate records cannot be caused by the difference in plate thickness. Lastly, it should be mentioned that post-test inspection showed that the plates had undergone some local indentation at the center where the balsa followers attached, indicating that even these light followers had sufficient inertia to mechanically deform the plates and that, perhaps, follower inertia effects may have contributed to some of the anomalies present in the test records.

As for computed results, those assuming constant pressure appear to reproduce the profiles of the test histories best, although they typically overpredicted deflections. The piston theory correction tended to dampen oscillations, so that the profiles do not match the OPTRON data as closely as the constant pressure calculations, but on the average give a better prediction of the magnitudes of the deflections. The addition of strain rate hardening dampened the profiles even more and, moreover, in all cases underpredicts experimental deflections. Computationally, however, the strain rate hardening model performed very well and did not exhibiting the erratic oscillatory behavior reported by Huffington and Wortman[15], which forced them to replace equation (1) by a more smoothly transitioning function.

Comparing the deflections at the first maxima, the salient features of the study are summarized in Table 1 and Figure 13. In all cases, the average pressure calculations overpredicted maximum deflections, while the addition of strain rate hardening to the piston theory calculations resulted in consistently underpredicting deflections. On the average, the calculations that involved correcting the reflected pressures for plate motion gave the best correlation, although scatter is considerable. Somewhat puzzling is the opposite trends exhibited by the maximum deflection data for the two plate thicknesses in Figure 13. While in the case of the 0.508 mm specimens, a curve passing through the experimental points would slope less than any of the computed curves, the opposite is true for the 0.813 mm specimens. Like the scatter already alluded to, this appears to be symptomatic of the correlation achieved in this study. It is not clear what the source of this discrepancy might be without further experimentation. Although one source for the observed scatter is probably variations in the material properties of the plates, it is hard to believe this was enough to cause such large discrepancies. A more likely source is natural scatter in reproducing data experimentally, but without further testing it is impossible to quantify this in terms of error bounds. One thing is clear, future tests should be conducted with engineering material manufactured with better quality control to assure reproducibility of material parameters and tests should be repeated at the same loading levels to establish error bounds.

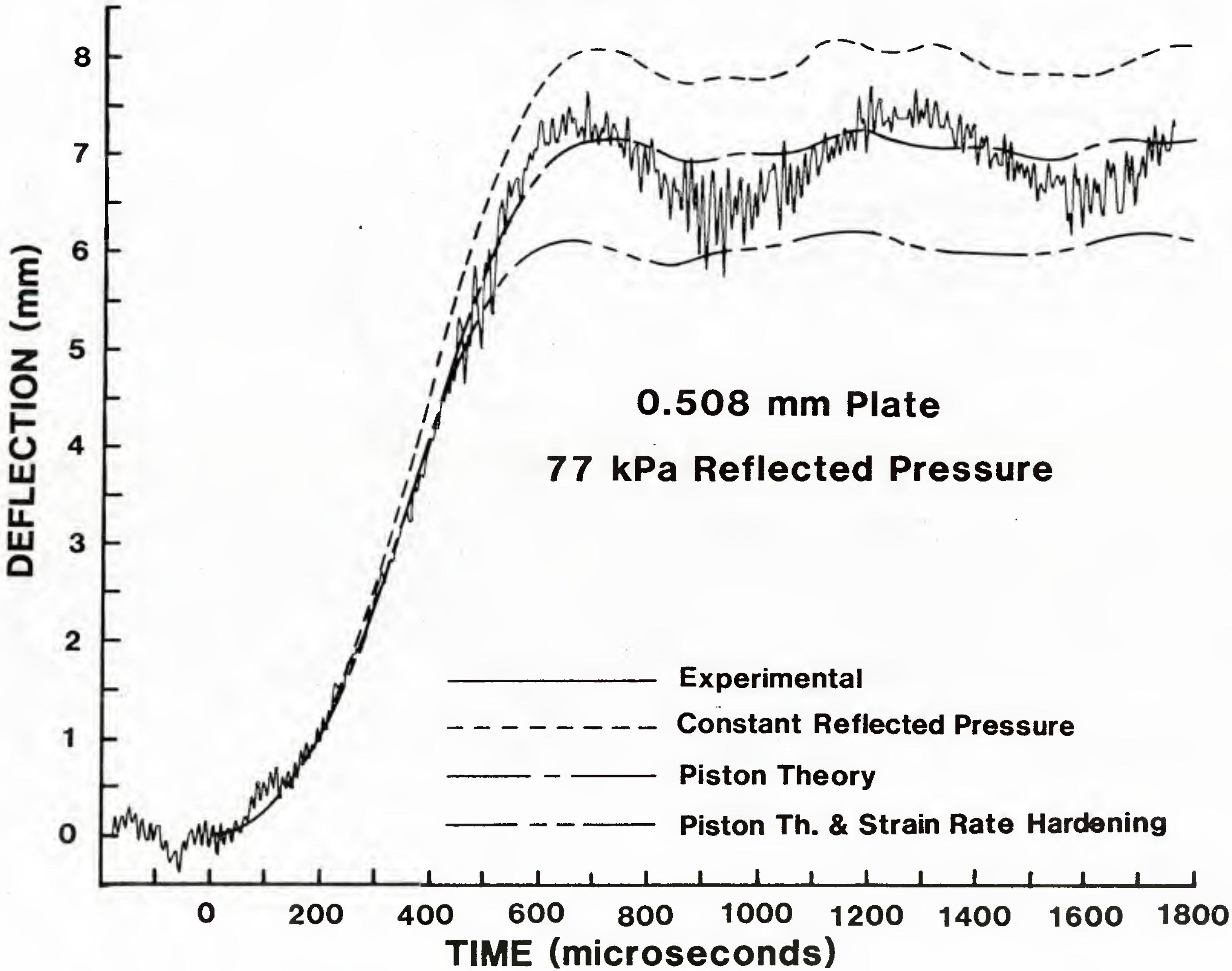

Figure 7. Comparison of computer and experimental deflection histories for 0.508 mm plate at 77 kPa reflected pressure.

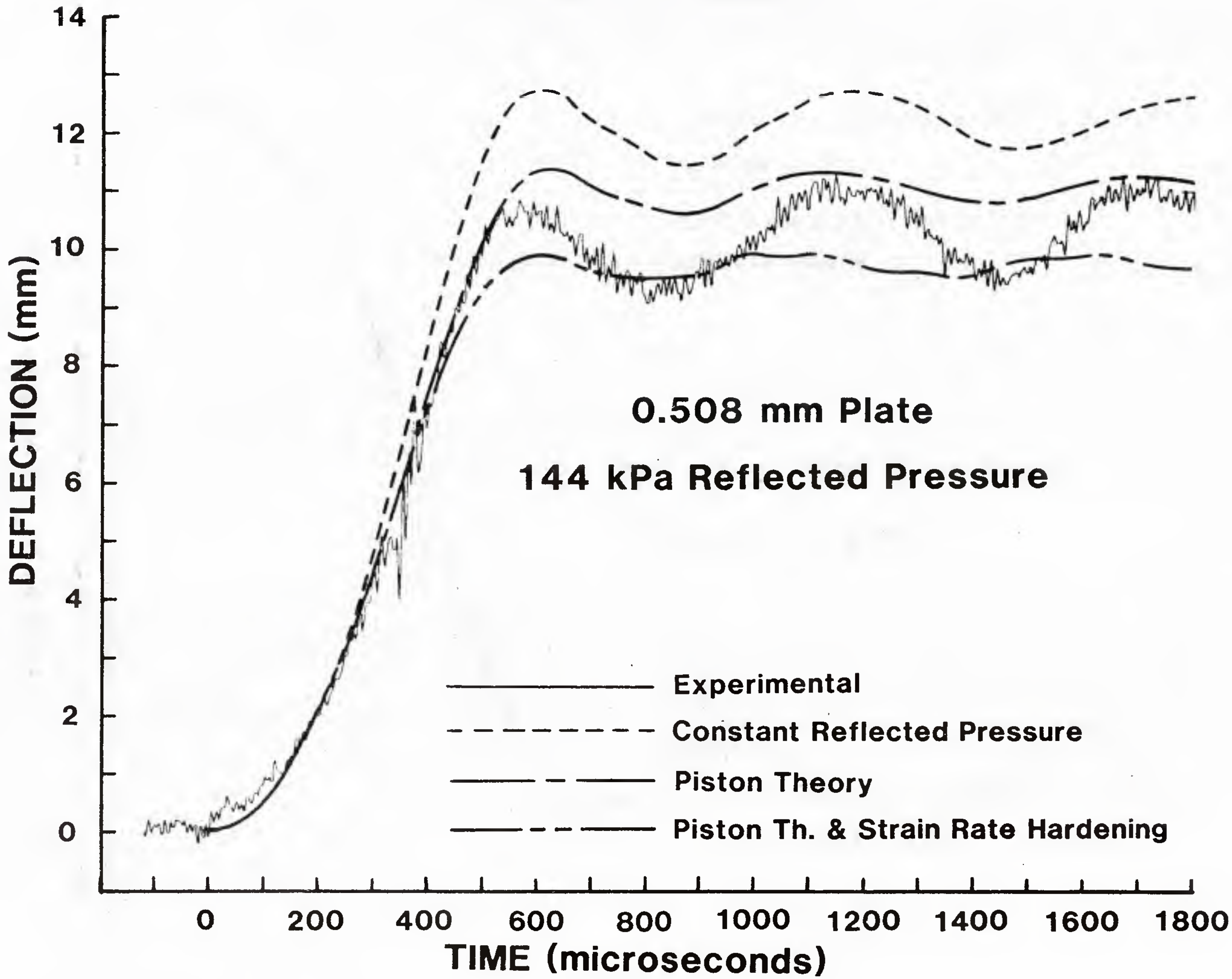

Figure 8. Comparison of computer and experimental deflection histories for 0.508 mm plate at 144 kPa reflected pressure.

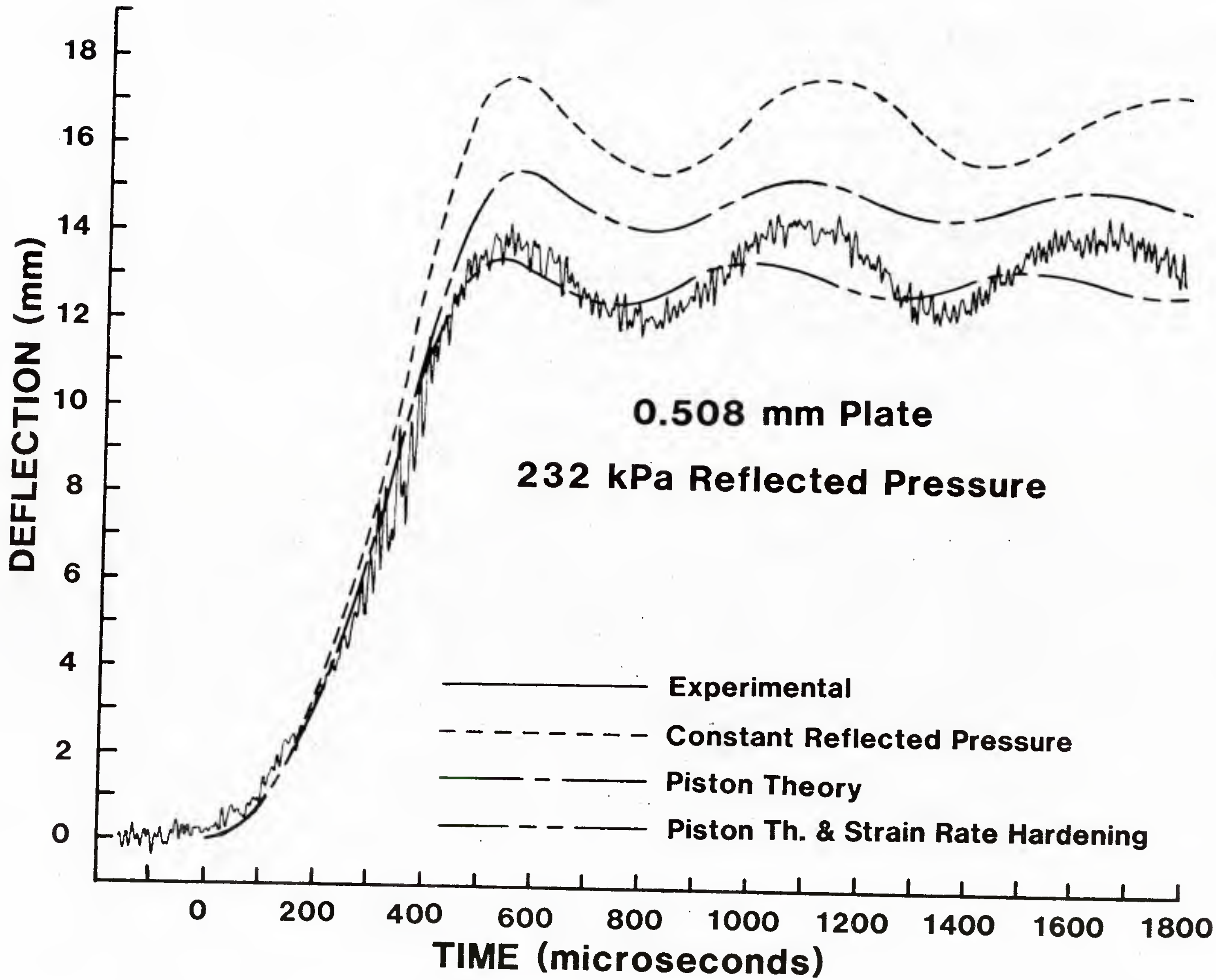

Figure 9. Comparison of computer and experimental deflection histories for 0.508 mm plate at 232 kPa reflected pressure.

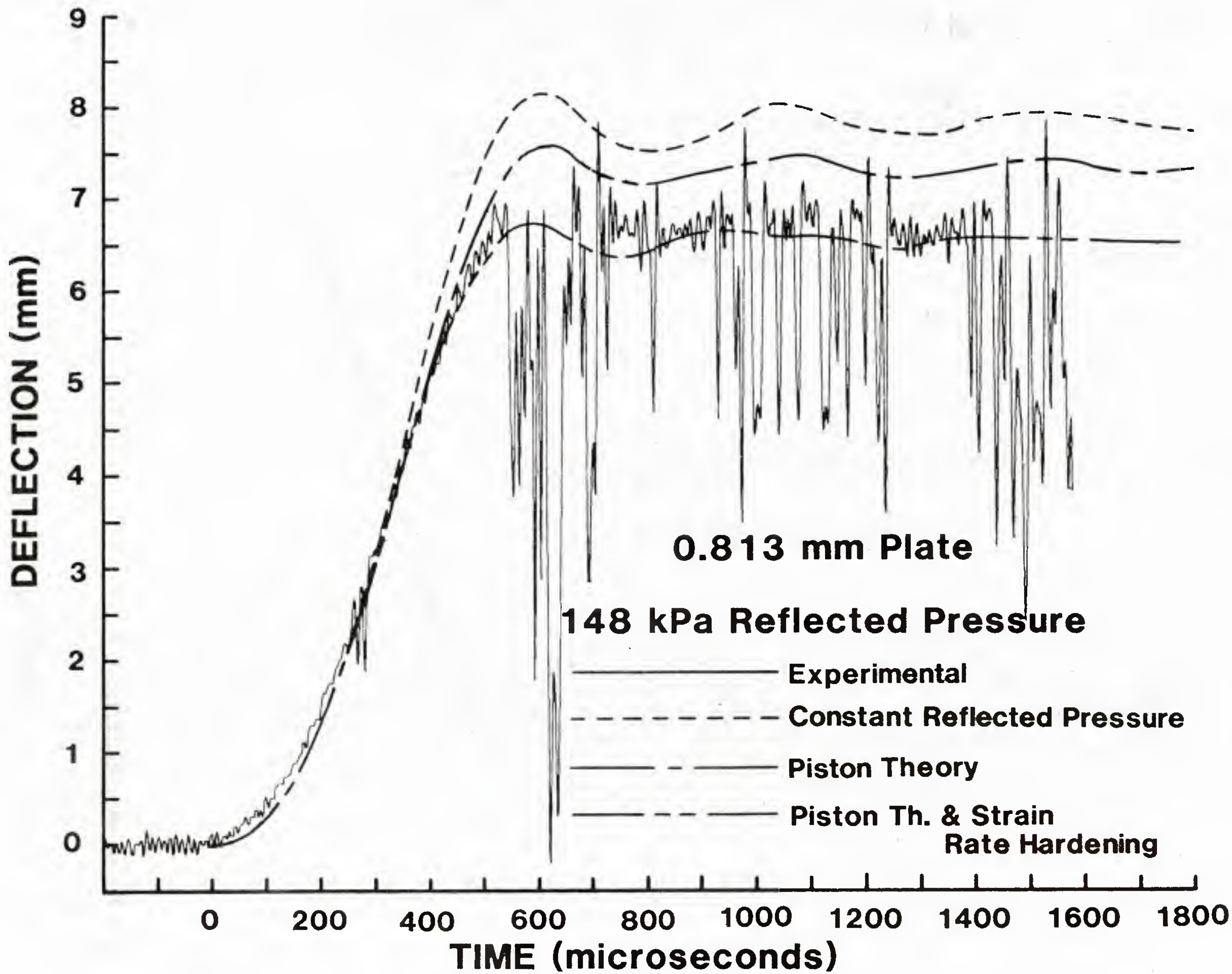

Figure 10. Comparison of computer and experimental deflection histories for 0.813 mm plate at 148 kPa reflected pressure.

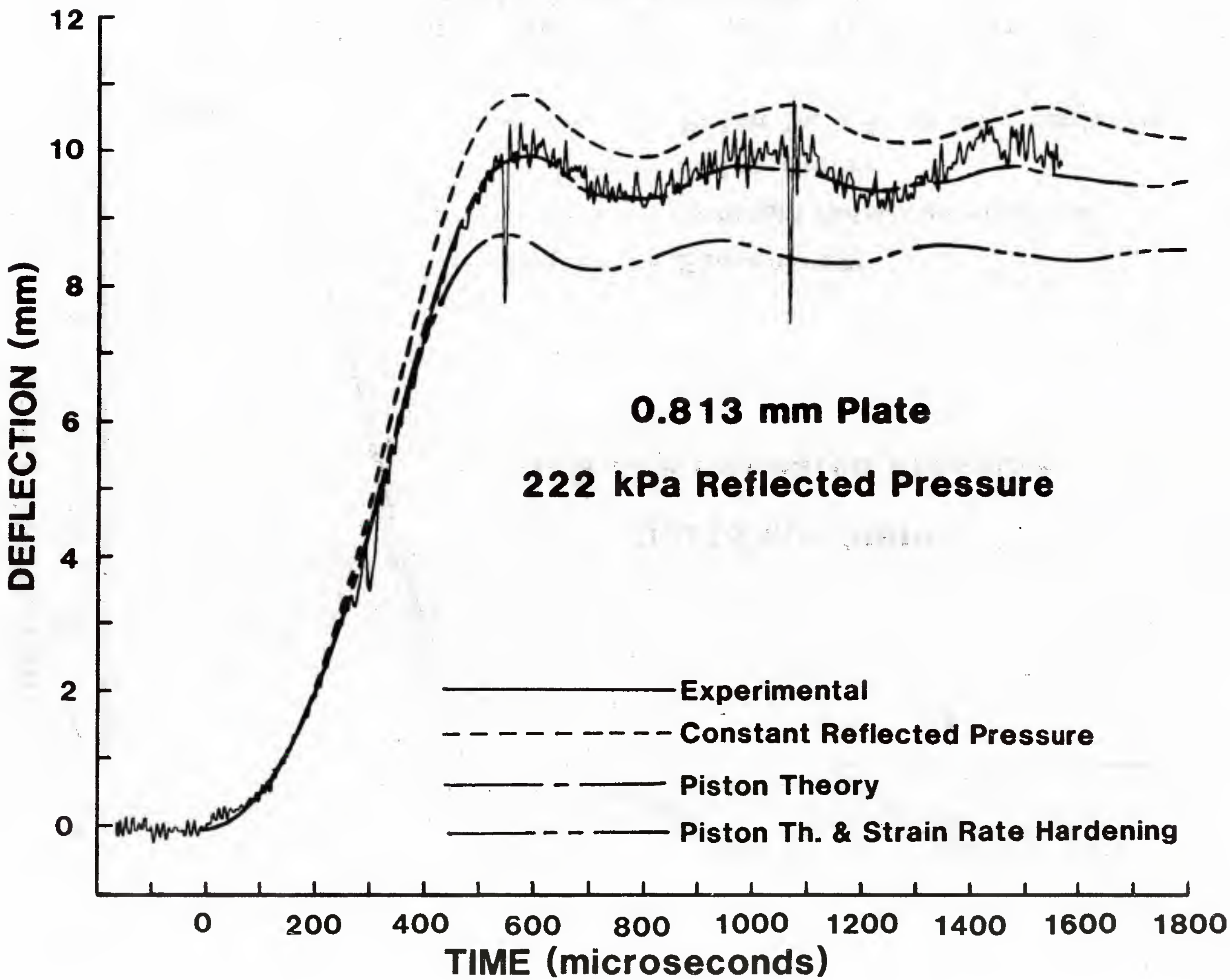

Figure 11. Comparison of computer and experimental deflection histories for 0.813 mm plate at 222 kPa reflected pressure.

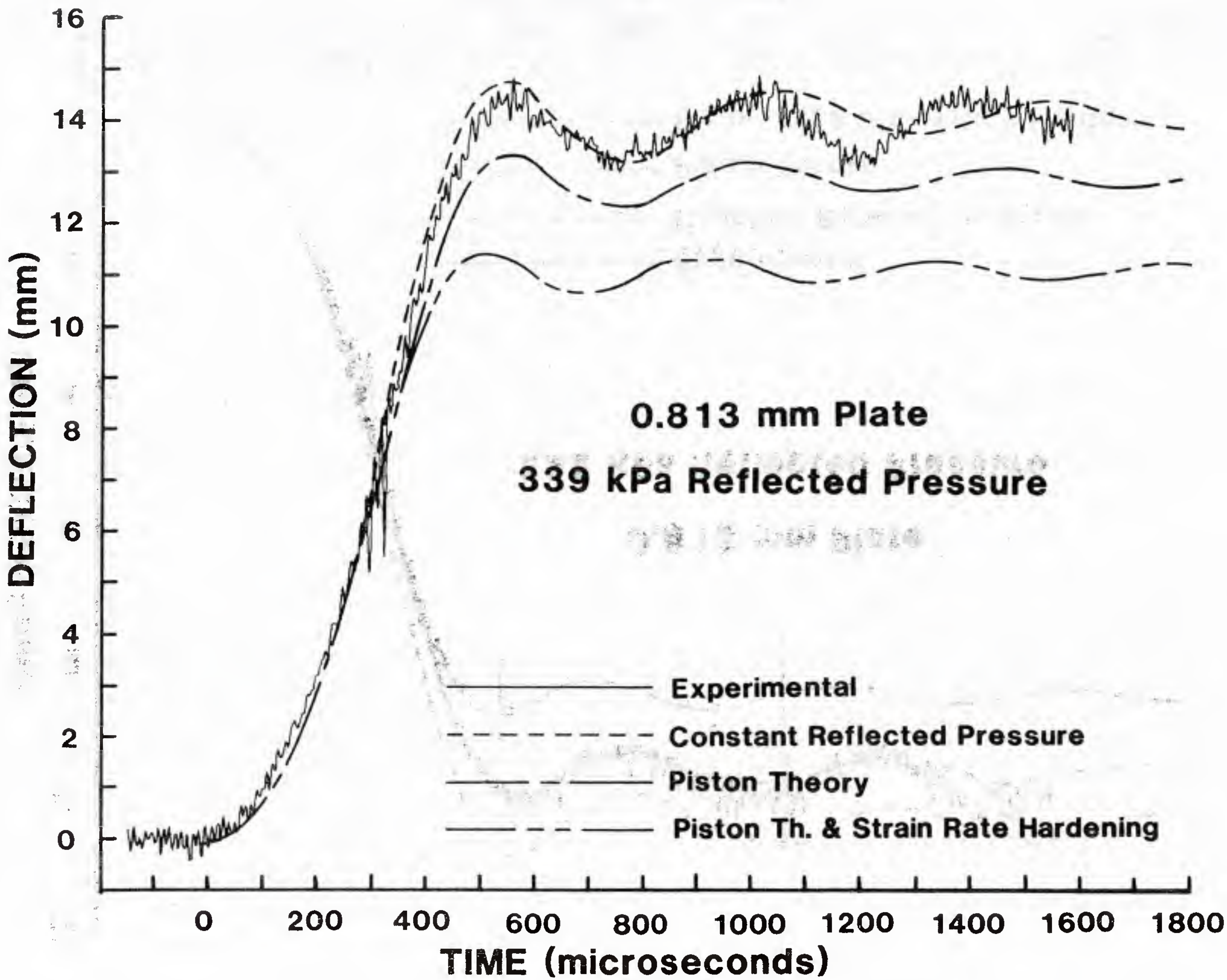

Figure 12. Comparison of computer and experimental deflection histories for 0.813 mm plate at 339 kPa reflected pressure.

TABLE 1. Comparison of first maxima of deflections.

Specimen Thickness mm (in.)	Reflected Pressure kPa (psi)	MAXIMUM DEFLECTIONS-millimeters			
		Experiment OPTRON	Finite-Difference Calculations		
			Nominal Pressure	Piston Theory	Piston Th. + Strain Rate
0.508 (0.020)	77 (11.1)	7.4	8.06	7.14	6.12
0.508 (0.020)	144 (20.9)	10.6	12.77	11.38	9.88
0.508 (0.020)	232 (33.7)	13.8	17.60	15.45	13.45
0.813 (0.032)	148 (21.5)	7.0	8.14	7.58	6.73
0.813 (0.032)	222 (32.2)	10.1	10.82	9.92	8.75
0.813 (0.032)	339 (49.1)	14.5	14.78	13.35	11.42

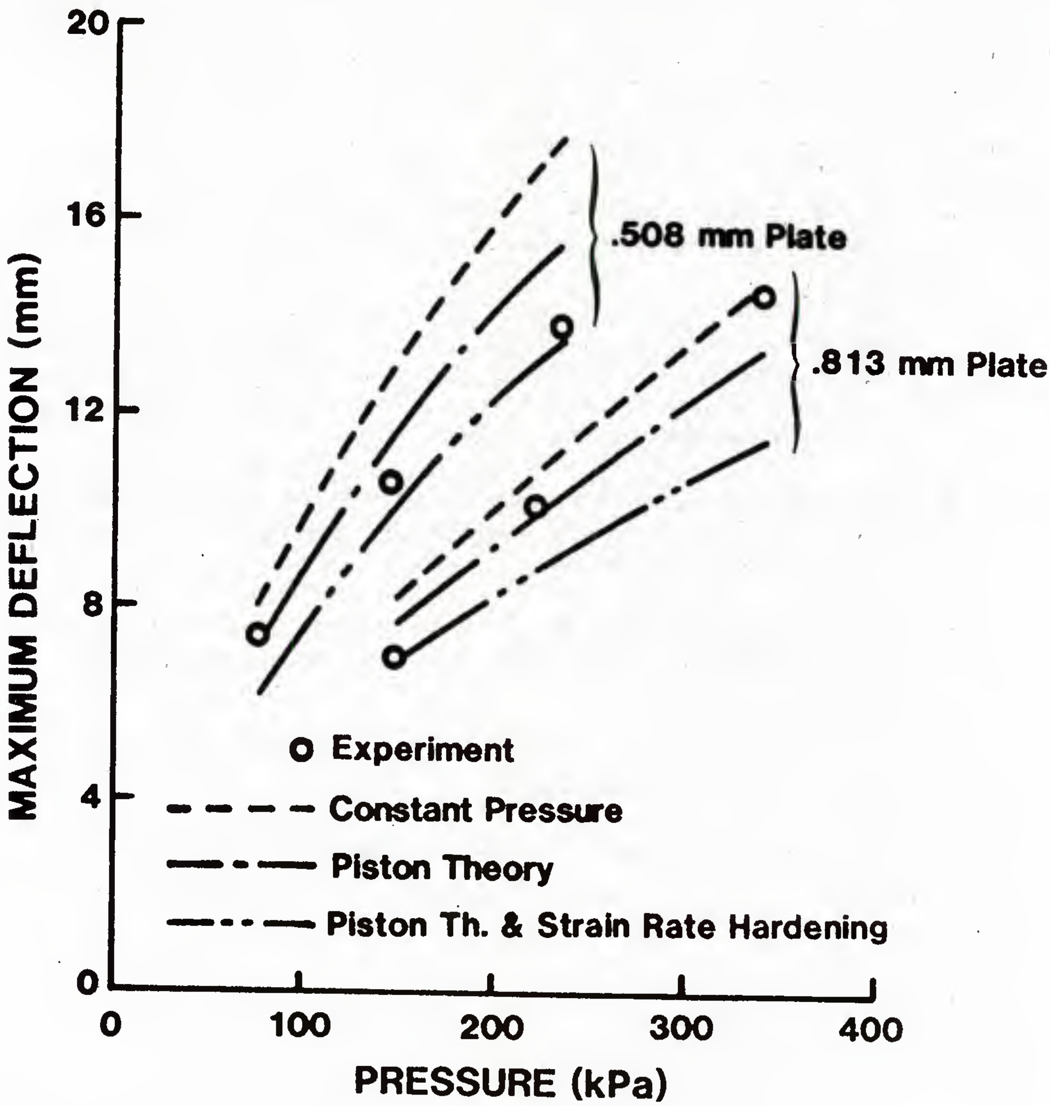

Figure 13. Summary of correlation between computed and experimental maximum deflections.

7. CONCLUSIONS AND RECOMMENDATIONS

This study has shown that the small shock tube can be a useful facility for performing precise structural response experiments. Also, such facilities usually can provide better support for detailed instrumenting of experiments than field testing. Moreover, with care, boundary conditions can be accurately replicated. As long as deflections are small, fluid-structure interaction can be ignored and nominal values of the loads can be employed. When deformations become moderately large, a simple fluid-structure interaction model, such as the piston theory used in this study, is sufficient to correct variations in the loading from nominal values.

In general, the OPTRON instrument recorded the motion of the follower accurately. Except for one case (0.813 mm thickness and 148 kPa pressure), where perhaps there was a problem with the follower not being securely anchored, the noise levels did not unduly interfere with interpreting the records. Use of balsa followers was not very successful. In addition to the problem caused by the followers having enough inertia to locally indent the plates, there may have been a problem with securely fastening them. The indentation caused by their inertia probably reduced the maximum recorded deflections, but the magnitude of this effect is difficult to quantify after the fact. Hence, in the future this problem could be avoided by the use of a massless follower, perhaps by the painting a demarcation on the plate's surface.

The conclusions drawn from the study can be summarized as follows:

- the small shock tube is a useful research tool for performing inexpensive, precision transient response experiments,
- the nominal value of the pressure loading on a thin plate undergoing moderately large transient deflections can be significantly altered by the plate's motion, so that some correction, such as provided in this study by piston theory, is necessary to accurately calculate the deflections,
- future use of engineering materials with better quality control of physical properties should improve the correlation between test results and calculations,
- the performance of the OPTRON instrument was acceptable, but perhaps better anchoring might reduce the noise observed in some records,
- the use of followers, no matter how light weight, should be replaced by some massless optical means,
- tests should be duplicated in order to establish error bounds.

REFERENCES

1. Santiago, J. M., and Shehata, B. I., "Structural Response of the SATCOM Antenna," *Proc. 17th Asilomar Conf.*, May 30 - June 3, 1983, Lawrence Livermore Laboratory, University of California, Livermore, CA, pp. 132-137.

2. Witmer, E. A., Merlis, F., and Pirotin, S. D., *Experimental Studies of Explosively-Induced Large Deformations of Flat Circular 2024-0 Aluminum Plates with Clamped Edges and of Free Thin Cylindrical 6061-T6 Shells*," Jan. 74, BRL Contract Report No. 134 (ASRL TR 152-5), U.S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, MD.

3. Houlston, R., and DesRochers, C. G., "Nonlinear Structural Response of Ship Panels Subjected to Air Blast Loading," *Proc. 6th ADINA Conf.*, M.I.T., 10-12 June 87, published as special issue of *Computers & Structures*, Vol. 26, No. 1/2, pp. 1-15.

4. Huffington, N. J., Jr., and Ewing, W. O., *Reflected Impulse Near Spherical Charges*, BRL Technical Report BRL-TR-2678, Sept. 85, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD.

5. Santiago, J. M., Klaus, M. H., and Wisniewski, H. L., "Finite Element Dynamic Analysis of a Blast Loaded Cylinder," *Advances in Impact, Blast, Ballistics, and Dynamic Analysis of Structures*, PVP-Vol. 106, Jul. 86, American Society of Mechanical Engineers, pp. 1-9.

6. Coulter, G. A., and Bertrand, B. P., *BRL Shock Tube Facility for the Simulation of Air Blast Effects*, BRL Memorandum Report No. 1685, Aug. 65, U.S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, MD.

7. Company Manual, *Model 501 Optical Displacement Follower*, OPTRON, Division of U.N.I.V. Technology, Inc., 30 Hazel Terr., Woodbridge, CT

8. Santiago, J. M., Wisniewski, H. L., and Huffington, N. J., Jr., *A User's Manual for the REPSIL Code*, BRL Report No. 1744, Oct. 74, U.S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, MD.

9. Wortman, J. D., *RPSL1D (A One-Dimensional Version of REPSIL)*, BRL Report ARBRL-MR-03221, Nov. 82, U.S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, MD.

10. *Underwater Explosion Research, A Compendium of British and American Reports, Volume III - The Damage Process*, Office of Naval Research, Dept. of the Navy, 1950.

11. Richtmyer, R. D., and Morton, K. W., *Difference Methods for Initial-Value Problems*, Interscience Publishers, New York, 1957, pp. 263, 274.

12. Santiago, J. M., and Wisniewski, H. L., "Implementing the Besseling-White Plasticity Model in the ADINA Finite Element Program," *Numerical Methods in Industrial Forming Processes*, Pineridge Press, Swansea, U.K., 1982, pp. 435-447.

13. Morino, L., Leech, J. W., and Witmer, E. A., *PETROS 2: A New Finite-Difference Method and Program for the Calculation of Large Elastic-Plastic Dynamically-Induced Deformations of General Thin Shells*, Dec. 69, BRL Contract Report No. 12 (ASRL TR 152-1), U.S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, MD.

14. Fung, Y. C., *Foundations of Solid Mechanics*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1965, pp. 58, 91.

15. Huffington, Jr., J. N., and Wortman, J. D., *Boundary Conditions and Strain-Rate Effects on the Response of Blast-Loaded Beams*, BRL Technical Report No. ARBRL-TR-02551, Mar. 84, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD.

16. Symonds, P. S., "Viscoplastic Behavior in Response of Structures to Dynamic Loading," *Behavior of Materials Under Dynamic Loading*, N. J. Huffington, Jr., Editor, ASME, 1965.

17. Huffington, Jr., J. N., Private communication, October 1987.

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